# Gravitationally bound quantum states of neutrons: applications and perspectives

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**Abstract.** Gravitationally bound quantum states of matter were observed recently due to unique properties of ultracold neutrons. We discuss here the actual status and possible improvements in this experiment. This phenomenon could be useful for various domains ranging from the physics of elementary particles and fields, to surface studies, or to foundations of quantum mechanics.

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## INTRODUCTION

Quantum states of a particle above a mirror in the gravitational field are described in textbooks on quantum mechanics (see for instance [1, 2]). However, they were discovered only recently using ultracold neutrons (UCN) [3-7]. The energy values and wave functions in such a system depend on the gravitational acceleration $g$ and on fundamental constants; a mirror can be approximated as an infinitely high and sharp potential step. This allows one to use this phenomenon for precision experiments.

## INTEGRAL MODE

The experimental scheme in a so-called integral mode [7] is shown in Fig. 1. The neutron flux through a slit between a mirror and a scatterer is measured in function of the slit size. The horizontal motion of neutrons is ruled by the classical laws, while in the vertical direction one observes the quantum effects.

Results are presented in Fig. 2. They confirm existence of the quantum states and allow us to estimate their parameters with the precision of ~10%. As shown in [7] an increase in accuracy is possible but strongly limited because of the smooth dependence on height of penetrability of the gravitational barrier between a classically allowed region for UCN and a scatterer height.
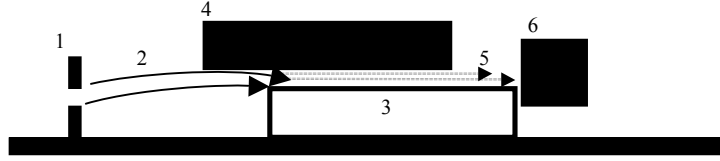
**FIGURE 1.** Flow-through integral mode. From left to the right: an input collimator (1); classical neutron trajectories (2); a mirror (3) and a scatterer (4). The dotted horizontal arrows illustrate the quantum motion of neutrons above a mirror (5), the black box presents a neutron detector (6).
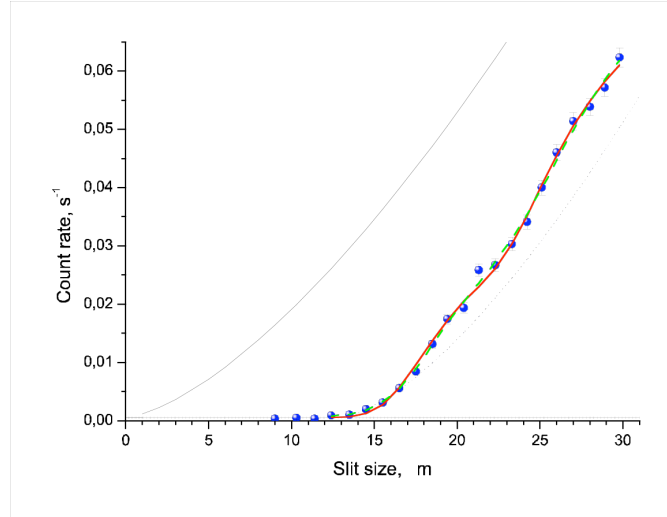


**FIGURE 2.** The neutron flux is measured in function of the slit size. The solid curve corresponds to the classical expectation. The dotted line illustrates a simplified quantum-mechanical dependence, which assumes existence of the lowest quantum state alone and the classical asymptotics at larger slit sizes. The dashed curve approximates the experimental data with a quantum-mechanical dependence.
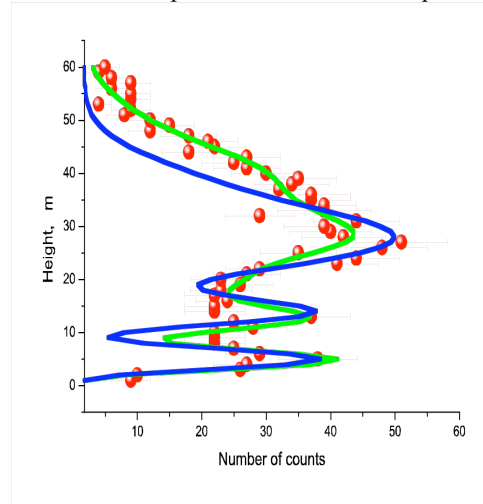


**FIGURE 3.** The neutron density is measured in function of height. The circles indicate the data. The dark and light solid curves correspond to the expectation for the ideal and realistic energy resolution.

# DIFFERENTIAL MODE

A differential measurement of spatial density in the neutron standing wave above a mirror has higher statistical sensitivity than the presented integral measurement. Besides, the quantum states are not modified by a scatterer, as in the previous case. For such a measurement we developed a special position-sensitive neutron detector of very high resolution [4]. As one can see in Fig. 3, the spatial resolution could be sufficiently high to identify the expected variation of neutron density.

# RESONANCE TRANSITIONS

We are going to considerably increase precision of these experiments using the method of resonance transitions between the neutron quantum states in the gravitational field [10]. It uses long storage of UCN in quantum states and therefore precisely defined their energies; it would provide a tool for a broad range of research such as for the elementary particles and fundamental interactions, foundations of quantum mechanics, surface physics, and in methodical applications.

# CONCLUSION

We discussed the experimental results [4-7] confirming existence of the gravitationally bound quantum states of neutrons. The achieved accuracy in the differential and integral modes is sufficient for some application of this experiment in different domains as discussed in [8-9]. Further improvements are possible, in particular due to the method of resonance transitions between the gravitationally bound quantum states of neutrons.

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